null mutation is associated with both leber congenital amaurosis and a normal ocular phenotype...
the first year of life, pendular nystagmus, and an extinguished or extremely attenuated photopic and scotopic ERG. The family members were also examined clinically, and one individual underwent the same ERG evaluation. All ERGs were performed using an International Society for Clinical Electrophysiology of Vision standard technique in accordance with institutional guidelines.

**Mutation Analysis**

Genomic DNA was prepared from peripheral blood by phenol-chloroform extraction or using the QIamp blood kit (Qiagen, Santa Clarita, CA) according to manufacturer’s instructions. Polymerase chain reaction (PCR) amplification was obtained from genomic DNA using previously published sets of primers. After PCR amplification, fragments were analyzed on an 8% polyacrylamide gel and visualized by ethidium bromide staining. To sequence the amplimers individually, these were separated on a 1.6% low-melting-point agarose, and the bands were excised and treated with β-agarase and subsequently phenol-chloroform purified. The purified products were used for direct manual sequencing using a cycle sequencing kit with 33P-labeled dideoxy nucleotides (Thermo Sequenase; Amer sham, Life Sciences, Arlington, IL), according to the manufacturer’s instructions. To further confirm the mutations, the gel purified amplimers were cloned into the pCR 2.1-TOPO vector, using the TOPO TA cloning kit (Invitrogen, Carlsbad, CA) according to the manufacturer’s recommendations. For each of the two probands, 10 different amplimer subcloned fragments were sequenced at the Johns Hopkins University core facility, using the ABI 100, version 3.2 automated sequencer (ABI prism; Applied Biosystems, Foster City, CA).

**RESULTS**

We sequenced the human CRX gene in 74 patients with the diagnosis of LCA. Analysis revealed the presence of two previously unreported heterozygous mutations in two unrelated patients; one was a 1-bp insertion c.25insG (GenBank accession number AF024711) causing a frameshift in codon 9 (P9ins1bp; Figs. 1 and 2A) and the second a 1-bp deletion, c.709delC, causing a frameshift in codon 237 (L237Δ1bp; Fig. 2B). No missense, nonsense or splice-site mutations were identified in this group. Both mutations cause frameshifts that predict significant changes in protein structure (Fig. 3).

In the case of P9ins1bp, the predicted protein is without all three conserved motifs: homeodomain, the WSP motif, and the OTX tail, a conserved motif near the C-terminus. Only the first nine amino acids of the 299-amino acid CRX protein remain unchanged by the frameshift, whereas the remainder of the protein is replaced by an out-of-frame polypeptide of 69 amino acids.

A very different situation is provided by the L237Δ1bp frameshift mutation. In this case, the predicted protein does not have 21% of the C-terminal tail, including the conserved OTX tail motif and C-terminus. This frameshift eliminates the original stop codon. The missing amino acids are replaced by a new C-terminus that determines a 369-amino acid protein derived from an alternate reading frame and the normal 3’ untranslated region. These mutations were not found in the CRX gene of 208 control individuals. These two patients also were screened for mutations in GUCY2D and RPE65, but the results were negative.

Sequence analysis demonstrated that the c.709delC mutation was absent in both parents, who had normal visual function, indicating its de novo origin in association with the disease. Ophthalmoscopic examination of the 18-month-old proband was unremarkable; however, the ERG was abolished. In contrast, sequence analysis showed that the father of the proband with the c.25insG allele also carried this insertion mutation. It should be underscored that in both cases parentage was tested and confirmed. A surprising finding was that the father who carried the c.25insG mutation did not show any
significant clinical abnormalities. Ophthalmologic examination of the fundus, fluorescein angiography, and color testing all produced normal results. ERG results revealed normal scotopic responses and only a very mild reduction in the photopic flash responses. This ERG profile is also observed in a significant percentage of normal individuals in the same age group. Another surprising feature is the finding that, since birth, the proband had had severe bilateral sensorineural hearing loss for all frequency ranges.

**DISCUSSION**

We have identified two new heterozygous mutations in the CRX gene of patients with LCA. Both sequence changes, c.25insG and c.709delC, cause frameshifts and predict significant protein changes. It is possible that the G-insertion mutation, c.25insG, has arisen de novo from polymerase slippage, because single-nucleotide DNA stretches show a tendency toward polymorphism. The c.25insG mutation is of special interest because all conserved functional motifs are missing and therefore represents the first convincing example of a CRX null allele. The c.25insG allele was also found in the proband’s father, who is phenotypically normal. This is in striking contrast to previously described CRX mutations found in patients with LCA. In each of these cases, a de novo heterozygous truncation mutation of the CRX gene was associated with disease. However, at the protein level, all these earlier published mutations, as well as the c.709delC mutation, leave the DNA-binding homeodomain intact.

The observation that a heterozygous null mutation such as c.25insG has no obvious phenotype eliminates haploinsufficiency as the disease-causing mechanism. However, we cannot exclude the presence of mutations outside the coding regions of the other, maternal CRX allele. Such mutations may affect promoter function and splicing or reduce the stability of the mRNA. Any of these possibilities would be consistent with an autosomal recessive model and could account for the dramatic differences in phenotype observed between the father and the proband. Another possible explanation is digenic inheritance (e.g., with the NRL gene)—specifically, double heterozygosity of two interacting mutations. In this context, we also screened for mutations in GUCY2D and RPE65 genes known to cause LCA and found no sequence changes. We could also conceive that a variant of the CRX promoter produces higher than normal levels of mRNA of the wild-type allele, suppressing disease in the father by boosting CRX protein above a critical threshold. Other explanations for this phenotypic variation include the possibility of somatic mosaicism in the father, genetic imprinting of the wild-type CRX allele, or environmental factors that could influence the normal course of retinal development and enhance the effect of the mutant allele.

In contrast, the c.709delC allele will produce a protein that has retained its DNA-binding homeodomain but has lost its OTX-conserved motif and C-terminal domain. This mutation closely fits the category described earlier by Freund et al. for which haploinsufficiency and dominant-negative effects were discussed as possible disease-causing mechanisms.
studies of the PAX6 protein have recently demonstrated that truncation mutations in the C-terminal transactivation region of PAX6 result in dominant-negative mutants. By analogy with the PAX6 studies, retention of the CRX homeodomain in the defective L237Δ1bp protein may allow it to compete for DNA binding sites with the functional wild-type transcription factor. Biochemical studies should give insight to the functional consequences of this mutation. These new findings bring a new perspective to the role of heterozygous CRX mutations in ocular disease and reinforce the need for caution when genetic counseling is requested by patients and their families.

Acknowledgments

The authors thank the patients and their families for their participation; Danping Zhu, Karen Ann Klima, and Thomas N. Mitchell for their support; and Donald J. Zack for helpful discussions.

References